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14. ABSTRACT
During the above-noted period of this Final Technical Report, the following salient milestones were reached: (1) Introduced and demonstrated the concept of injecting electrons into the quantum dot (QD) active infra-red absorbing region from bracketing doped contact layers (to suppress unwanted dark current) leaving the QD region undoped; (2) Introduced and demonstrated the benefits of the concepts of (a) strain-relieving QD capping layers, (b) current blocking layers, and (c) lateral potential confinement layer for tailoring the QD electronic response to the desired IR response; (3) Demonstrated high performance QDIP devices in the mid and longwavelength IR regions; (4) Demonstrated voltage-tunable mid and long IR dual wavelength QDIPs.

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Stress-Engineered Quantum Dots for Multispectral Infra-red Detector Arrays

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This final technical report summarizes the salient accomplishments of the work on self-assembled quantum dot synthesis, tailoring of their electronic properties, and the exploitation of such properties for realization of high performance quantum dot infrared photodetectors (QDIPs) carried under the above noted contract during the period July 1, 1998, through June 30, 2006.

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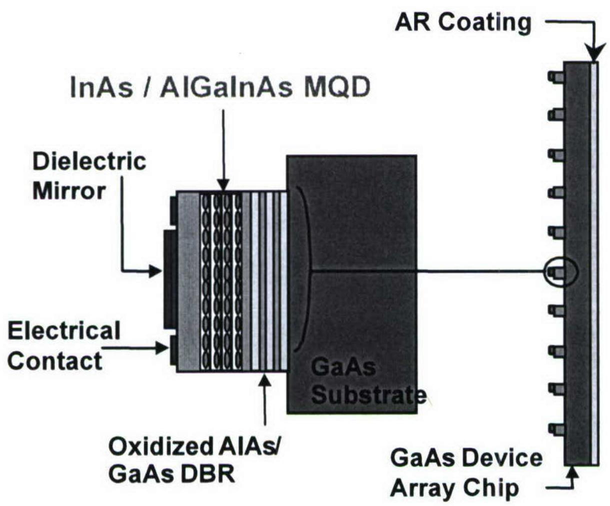
I. Preamble and Objectives

This Final Technical Report on AFOSR grant number F49620-98-1-0474 summarizes the major accomplishments of the multi-investigator team led by A. Madhukar as the PI and comprising Co-PIs J. C. Campbell (Univ. of Texas, Austin), W. Wang (Columbia University), Y. C. Chang (Univ. of Illinois, Champaign-Urbana), and D. H. Rich (USC, 1998-2003) for the period July 1, 1998 to June 30, 2004, and reduced to A. Madhukar and J. C. Campbell (at the University of Virginia since Jan 1, 2006) from July 1, 2004 until June 30, 2006. Briefly, the overall objectives of this program were:

(1) Explore epitaxical island semiconductor quantum dot, [also dubbed self-assembled quantum dot (SAQD)] science and the concept of stress engineering, and

(2) Examine and assess the potential of such stress-engineered quantum dots (QDs) as active regions of infra-red photodetector arrays (QDIPs).

A pictorial representation of the aimed - for QDIP array is shown below. The salient accomplishments are summarized in Section II. This is followed by the List of Publications in Section III and the List of Personnel supported by this grant in Section IV.



Schematic of SAQD-based infrared photodetectors for the 1-12μm range.

II. Summary of Salient Accomplishments

(A) Quantum dot growth, structure, and optical property related:

1. Successfully grew GaAs, InGaAs and InAlGaAs capped InAs on GaAs(001) QDs up to ten layer stacking which show low structural defect (threading dislocation, stacking fault) density and correspondingly high PL efficiency and narrow PL linewidth [publications 1, 15, 17, 18, 21-24].

2. Introduced QDIP structures synthesized using migration enhanced epitaxy based capping of InAs quantum dots at very low (~350°C or less) temperatures to minimize compositional mixing [publications 15, 16].

3. Introduced undoped quantum dot region based QDIP structures with electron injection from n-doped contact layers and, using PL/PLE and photocurrent optical spectroscopy, demonstrated that the electron ground states of the InAs/GaAs(001) QDs in such n-i-n photodetector structures are partially occupied indeed [publications 15, 16].

4. Introduced and exploited the notion of quantum dots buried in compositionally graded capping layers to manipulate the chemical band edge discontinuities and strain distribution to tailor the intraband electronic states [publications 21-24]. (This approach has subsequently been dubbed "quantum dots in-a-well")

5. Demonstrated *selective tailoring* of the QD electronic energy levels and wave function through introduction of the idea of placing a lateral potential confinement layer (LPCL) at different heights of islands in the InAs/$In_{0.15}Ga_{0.85}As$ QD system during capping of the InAs islands [publication 22].

6. Demonstrated unimodal intraband infrared photoresponse at 8-9 μm using InGaAs capped 2 ML InAs/GaAs(001) QDs in n-i(QDs)-n QDIP structure [publication 21, 23].

7. Demonstrated voltage-tunable QDIP structures with photocurrent response in the mid (3-6μm) and long (8-12μm) wavelength IR regimes [publication 24].

8. Demonstrated dual (mid and long IR) wavelength QD photoluminescence utilizing our previously introduced notion of VDA (variable deposition amount) stacking of differing average size QDs and utilizing the lateral potential confinement layer (LPCL). [unpublished]

9. Demonstrated for the first time the existence and orientation of intraband transition induced dipole moment in self-assembled InAs/GaAs(001) QDs. Simultaneously, the interband dipole moment is also determined [publication 25].

10. Observed temperature-dependence of intraband transition induced dipole moment in self-assembled InAs/GaAs(001) QDs [unpublished].

11. Utilized cathodoluminescence wavelength imaging (CLWI) technique to obtain SAQD images on the meso scale and found a higher-degree of uniformity for domains of the InGaAs capped InAs/GaAs(001) QDs than that of GaAs capped InAs/GaAs(001) QDs [publications 8, 11].

12. Studied the substrate orientation dependence of the formation of InSb quantum dots on on-axis and off-axis GaSb and AlGaSb [unpublished].

(B) Theory

1. Developed a state-of-the-art theoretical modeling code for SAQDs that includes InAs/GaAs SAQDs with different orientations. Have studied the detailed geometric dependence of electronic structures of SAQDs and the predicted optical

properties are consistent with the experimental findings noted above [publication 10].

2. Modeled dark and tunneling currents in quantum dot arrays [publications 7, 17, 20].

(C) Infrared detector device related:

1. Introduced QDIP device structures with undoped quantum dot region to minimize dark current [publications 15, 16].
2. Demonstrated unimodal intraband infrared photoresponse at 8-9 μm using InGaAs capped 2 ML InAs/GaAs(001) QDs in n-i(QDs)-n QDIP structure [publication 21, 23].
3. Demonstrated the first two-color, voltage tunable, QDIP photoresponse. Using InGaAs capped 2.5 ML InAs/GaAs(001) QDs in n-i(QDs)-n QDIP structure, photoresponse at ~5.5 μm and ~9 μm is demonstrated [publications 24, 26] .
4. Demonstrated QDIP devices with high detectivities at normal incidence. For InAs/GaAs QDIPs with AlGaAs blocking layers have achieved $D^*=1\times10^{10}$ $cmHz^{1/2}/W$, R= 14 mA/W at –0.7V bias and 77K [publications 27, 28].
5. Demonstrated unimodal QDIP devices with high responsivity of 22mA/W and detectivity of $3.2x10^9 cmHz^{1/2}/W$ at 77K and 8.3μm [publications 29, 30].
6. Demonstrated voltage tunable, multi-spectral response utilizing QDIP devices with 2.5ML InAs QDs with InGaAs cap layers and showed mid- and far-infrared detection with detectivities of 5.8×10^9 $cmHz^{1/2}/W$ and 7.3×10^8 $cmHz^{1/2}/W$ at 5.9 μm and 8.9 μm, respectively, at 77K publications [publication 31].
7. Demonstrated a two-color, voltage tunable intraband photoresponse of QDIP structures based on variable-deposition-amount stacking of InAs QDs [unpublished].
8. Examined the impact of current blocking AlGaAs layers in the InGaAs capped 2ML InAs QDIPs and found equal reduction in dark and photocurrents, thereby leaving the detectivity comparable to that obtained without the use of the current blocking layers [publication 27].
9. Demonstrated dual wavelength response at ~5μm and ~9.5μm in QDIPs containing a lateral potential confinement InAlGaAs layer in the capping layer [unpublished].
10. Calculated reflectivity and electric field distribution of mid infrared microcavities defined by Ge/SiO_2 and Au or GaAs/air and Au mirrors [unpublished].

III. List of Publications

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